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A Study of Direct Solar Radiation Transmission in Asymmetrical Multi-span Greenhouses using Scale Models and Simulation Models

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Abstract

Direct solar radiation transmission inside scale models of greenhouses with different roof slopes was measured and the results compared with calculations from a simulation model. Seven different roof slopes were tested, which had symmetrical and asymmetrical roof shapes: 8°–18°; 18°–8°; 27°–27°; 27°–45°; 36°–55°; 45°–27°; 55°–36° (8°–18° denoting that the south-facing slope was 8° and the north-facing one was 18°). Radiation transmission in scale models was quantified using linear solarimeters that integrated solar radiation along the cross-section of the span. The correlation between measured and calculated hourly and daily mean transmission values was good. Minor differences were attributed to the accumulation of dust and condensation on the scale models, two conditions that were not taken into account in the simulation model.

The results of the study showed that direct solar radiation transmission increased considerably as slope increased, up to a value close to 30°, especially in the winter months in which radiation was most limited. Assymetrical greenhouses did not always transmit more than symmetrical ones with similar slopes. In the cases studied, the scale model with 27-27° symmetrical roof had the highest winter transmission.

The use of scale models allowed different greenhouse structures to be characterised with respect to direct radiation transmission. This method can produce considerable savings of time and money and provides a realistic simulation of radiation transmission in full-scale greenhouses.

Nomenclature

A: absorption by a simple transparent sheet
C_{abs}: power-absorption coefficient, m^{-1}
D_{MB}: mean bias deviation
D_{RMS}: root-mean-square deviation
E: angle between the incident ray and the horizontal axis perpendicular to the greenhouse span, deg
E_S: standard error
F: reflectance of a single transparent sheet
L_1: south-facing surface of roof, m
L_2: north-facing surface of roof, m
l_a: segment of the beam of radiation that reaches the fourth module of a greenhouse at gutter height after travelling through the second and third modules of the same greenhouse, m
l_b: segment of the beam of radiation that reaches the fourth module of a greenhouse at gutter height after travelling through the first, second and third modules of the same greenhouse, m
l_1, l_2: portions of the beam of incident light travelling through the first side and the second side of the roof module
m: number of spans that intercept solar radiation
N: number of simulated or measured data
N: index of refraction
R_T: ratio of measured and calculated daily transmission
T: transmission for a single transparent sheet
T_{cal}: calculated material transmission
T_D: mean daily transmission
T_{exp}: mean daily measured transmission
T_{LE}: lengthwise greenhouse-part transmission
T_{MAT}: cover-material transmission
T_{meas}: measured material transmission
T_r: direct radiation reflected by a greenhouse roof surface and then transmitted
T_{sim}: mean daily simulated transmission
T_{TE}: crosswise greenhouse-part transmission
T_{TOTAL}: total direct radiation transmission
α: slope angle of the south-facing surface of the roof, deg
β: slope angle of the north-facing surface of the roof, deg

1. Introduction

One of the advantages of protected cultivation in Mediterranean regions is the high level of solar radiation that results from the many clear days in autumn and winter. However, the widespread use of low-cost greenhouses limits the level of radiation transmitted. Enhanced radiation transmission is regarded as a key objective for raising production quality and quantity (Cockshull, 1989; Castilla & López-Gálvez, 1994). Such transmission in greenhouses can be improved by using carefully designed roof geometry.

Various studies on radiation transmission models have been carried out for sophisticated greenhouses (Bot, 1983; Critten, 1993), but little attention has been paid to Mediterranean greenhouses. Recently, growers in the south of Spain have begun to replace old low-cost structures with new greenhouses in an attempt to increase light transmission in winter months, when produce prices are higher (Castilla & López-Gálvez, 1994). East–west orientation of saddle-roof greenhouses in Mediterranean latitudes is better than north–south for maximum light transmission in autumn and winter, as has been widely reported (Jaffrin & Urban, 1990; Kurata, 1990; Pieters, 1994; Papadopoulus & Pararajasingham, 1997; Papadakis *et al*., 1998; Giacomelli & Ting, 1999). There are, however, few publications on optimal roof slopes (Kozai *et al*., 1978).

When characterising radiation levels in a greenhouse, transmission through side walls needs to be taken into account. This is particularly true in single-span greenhouses (Papadakis *et al*., 1998). However, in large, commercial multi-span greenhouses, the quantity of radiation received by the side walls is very small in comparison with the total radiation received by the greenhouse and it is therefore not necessary to take it into consideration (Bot, 1983).

When quantifying radiation transmission, the spatial variability of radiation in greenhouses makes it necessary for measurements to be taken with spot sensors in the complete area of one span (Papadakis *et al*., 1998). When the variation in the radiation transmitted to different zones of the greenhouse is very great, or when it is necessary to simultaneously study the transmission of radiation from several different greenhouses, the number of spot sensors required may make the job of characterising impractical. Tube solarimeters integrate radiation data along a line and can provide a representative estimate of transmission. Tube solarimeters placed on a rotary device have been successfully used in glasshouses, where shade from structural elements and equipment can considerably influence radiation transmission (Heuvelink *et al*., 1995).

Mediterranean greenhouses in use in Southern Spain typically have fewer structural members in the roof, but they also suffer from non-uniform radiation transmission, due mainly to the different angle of incidence the radiation beam makes with the different surfaces of the roof. Taking measurements across all the spans in full-scale Mediterranean greenhouses is a time-consuming task and requires considerable equipment.

One approach to solve this problem is using scale models. This method has been used to quantify the ventilation performance of greenhouses (Boulard *et al*., 1998; Oca *et al*., 1999) and their radiation transmission (Schultz, 1955; Kurata, 1991; Li *et al*., 1995; Papadakis *et al*., 1998). Scale models can also be useful for validating simulation models. In some cases, scale-model measurements can be considered more representative than simulation models, because many of the assumptions and simplifications considered in calculations are avoided by direct measurement under more realistic conditions.

The objective of this study was to examine the advantages of using scale models as a means for studying the transmission of direct radiation in symmetrical and asymmetrical greenhouses. For this purpose, a number of scale models of greenhouses with different roof slopes were tested throughout the year. Tube solarimeters covering all the spans integrated the radiation transmitted by the greenhouse cover, and actual measurements were compared with calculations using a simulation model to verify the validity of the scale-model measurements.

2. Materials and methods

2.1. Scale models

Four saddle-roof multi-span greenhouse models (scale 1:15) were constructed, oriented east–west and tested at the Agricultural Research and Development Centre of Granada (CIFA) (latitude 37°10′N) in Southern Spain. To study all possible cases (Fig. 1, Table 1), the asymmetrical scale models were rotated 180° during the measuring period, *i.e*. the south-facing roof slope became north-facing, and vice versa. This was done because there were not enough tube solarimeters to allow simultaneous readings to be taken for the seven scale models.

Special attention was paid to the evaluation of asymmetrical models, since they are gaining popularity in Southern Mediterranean areas because of their potential to increase the solar radiation available for production (Castilla & López-Gálvez, 1994).

Each scale model consisted of three spans, each 110 cm long and 40 cm wide (representing a 6 m wide, full-scale model, typical of Mediterranean greenhouses. The length of 110 cm was chosen so that radiation would reach the sensors, although through the roof and not through the sides). The cover glass was 8 mm thick and was held in position by a metal support at both ends. This thickness was chosen to produce a glass sheet rigid enough to avoid the need for any supporting element along the length of the scale models. The floor was painted matt black to minimise reflections from the ground.

Total solar radiation was measured using tube solarimeters (TSL from Delta-T). Each sensor covered the full-width of the modules in the central span and the north span of each model. In this way, it was sought to prevent the possible entry of solar radiation through the south wall of the scale model and its incidence on the tube solarimeter. Measurements were taken at the height of the eaves and at what would have been the height of the gutter in a full-scale

greenhouse. Another tube solarimeter was placed in the open air, as was a pyranometer (Kipp & Zonen, CM6B), which was used for periodic calibration of the tube solarimeters. Solar radiation data were quantified in 10 min periods using a data logger (Campbell CR10). Solar radiation transmission was calculated for half-hour periods and for the whole day during clear-sky conditions from June 1998 to December 1999. In this study, 30 min periods were considered due to the need to reduce the volume of data generated by the transmission measurements and calculations relating to seven types of greenhouse and different times of the year.
An average value for transmission was therefore calculated every 30 min, which was based on instantly calculated values.

Regression analysis between measured and calculated transmissions was carried out for the scale models and for the time periods subject to evaluation (winter and summer solstices and spring and autumn equinoxes).

2.2. Transmission model

The transmission model for multi-span greenhouses developed by Bot (1983) was used to validate measurements taken in scale models. This transmission model allows for the calculation of direct and diffuse transmission at any given time. In the Mediterranean, diffuse radiation in sunny days is only a small part of the global solar radiation. Observations from neighbouring weather stations indicate that daily diffuse radiation is between 6 and 8% of the total daily radiation in sunny days. At noon this percentage is even lower. The task of measuring transmission from the greenhouses to diffused radiation on overcast days was undertaken at the beginning of this study. It was observed that during the central hours of the day, the amount of transmission to diffused light on overcast days was similar to total transmission (direct plus diffused) on sunny days. Thus, when measuring radiation transmission, the difference between transmission to direct radiation and to total radiation was only of the order of 1–2% during the first and last hours of daylight, and insignificant during the middle hours of the day (Soriano, 2002).

For the reasons previously cited and for the sake of simplicity, only direct radiation was considered in this study and therefore only Bot's sub-model for direct radiation transmission was used. However, Bot's model is not directly applicable to the calculation of transmission for asymmetrical greenhouses and its governing equations had to be adapted to cover this case. The adaptation of the calculating equations is presented in Appendix A.

The total transmission T_{TOTAL} is the product of transmission through the cover material (resulting transmission if there were only covering material without any kind of structure), T_{MAT} and transmission through the opaque roof parts, formed by the lengthwise parts such as the ridge and gutter (resulting transmission if there were only longitudinal structural elements, without any covering material or transversal elements), T_{LE} and the crosswise parts such as the glazing bars (transmission if there were only transversal structural elements), T_{TE}. The total transmission can therefore be written as:

$$(1)\quad T_{TOTAL}=T_{MAT}T_{LE}T_{TE}$$

Each component has its own sub-model that takes into account the geometry of the cover and the interaction between neighbouring spans in terms of direct radiation transmission and reflections from one to another.

For the sake of simplicity, the scale models were built without lengthwise or crosswise parts. The ridge in the scale models was formed by leaning one glass pane against another. This created an opaque area (similar to the shadow produced by a bar with a cross section with 8 mm long sides) that was taken into account in the calculation of T_{LE}. Since there were no transversal structural elements, the value for T_{TE} could be taken as 1.

The model was programmed in Fortran to provide transmission according to the position of the sun throughout the day, from dawn to dusk Instantaneous values were integrated to provide mean daily transmission values.

To calculate the transmission of the glazing material as a function of the angle of incidence, the simulation model applied the well-known Fresnel equations. This required prior determination of the index of refraction n and the power-absorption coefficient C_{abs} in m^{-1} that is a measure of the attenuation caused by absorption of solar radiation that results from its passage through the material. In order to do this, the direct radiation transmission of a glass sample was measured using a transmission goniometer developed at Silsoe Research Institute (Kamaruddin, 1999). This apparatus contained a tungsten-halogen lamp with a rotating mirror assembly to vary the angle of incidence of the beam with the glass sample. The angle of incidence was varied from 0 to 90° and the corresponding transmission values were measured. STATGRAPHICS software was then used to determine the best fit between measured transmission values and those calculated using the Fresnel equations, which meant n and C_{abs} could be determined (Montero *et al*., 2001).

2.3. Comparison of measurements and calculations

Two types of comparisons were carried out.

(1) Mean half-hour transmission values were determined for clear-sky conditions. Linear regressions of measured and calculated values were done for a set of four sunny days for each solstice/equinox (*i.e.* on or around the winter solstice, the summer solstice, the spring equinox and the autumn equinox).

(2) Mean daily transmission T_D, for sunny days were measured during a complete annual cycle. For this case, the ratio R_T of measured T_{exp} and calculated T_{sim} daily transmission for each scale model was obtained, as well as the standard error E_S for each case:

$$(2)\ R_T=\sum i=1N(T_{exp,i}/T_{sim,i})N$$

where N is the number of days for which transmission values were measured or calculated.

$$(3)\ ES=N\sum X^2-\sum X^2NN-1$$

where

$$X = T_{exp}/T_{sim} \quad (4)$$

The mean bias deviation D_{MB} and root-mean-square deviation D_{RMS} were also calculated (Foyo-Moreno *et al*., 2000):

$$DMB = \frac{1}{N}\sum_{i=1}^{N}(T_{sim,i} - T_{exp,i}) \quad (5)$$

$$DRMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(T_{sim,i} - T_{exp,i})^2} \quad (6)$$

2.4. Assessment of transmission for different roof slopes

The final task carried out in this study was the comparison of mean daily transmission for different roof slopes based on the measurements taken in different greenhouse models.

3. Results and discussion

3.1. Power-absorption coefficient and index of refraction for the glazing material

The results of laboratory measurements of direct radiation transmission as a function of the angle of incidence are shown in Fig. 2. As with most materials, transmission is highest for radiation perpendicular to the plane of the sample and gradually reduces as the angle of incidence increases. From these measured values, n and C_{abs} were determined from the equations of Fresnel and according to the procedure developed by Bot (1983). The calculus equations were programmed on a spreadsheet on which the values of n and C_{abs} varied in such a way as to minimise the difference between the measured transmission T_{meas} and the calculated transmission T_{cal}. The best fit was obtained with values for n of 1·6 and C_{abs} of 5·15. Agreement between T_{meas} and T_{cal} for the given coefficients is shown by the regression line between them. There was good agreement, as:

$$T_{means} = 1{\cdot}0001\,T_{cal} \quad (7)$$

with a value for the coefficient of determination R^2 of 0·9997.

These values of n and C_{abs} were used for subsequent calculations with the simulation model.

3.2. Comparison of mean half-hour transmissions for clear-sky conditions

For the sake of simplicity, only results from the scale model with an 8° slope on the south-facing side and an 18° slope on the north-facing side (8-18°) are shown in Fig. 3. Figure 3(*a*) compares measured and calculated transmission values for a clear day on or around the winter solstice (13th January), while Fig. 3(*b*) corresponds to a clear day on or around the summer solstice (19th June). The mean half-hourly total transmission measured in the scale models was very close to the simulation results. Nevertheless, the simulation model tended to produce higher values, the greatest differences being during the hours around midday, with better agreement at sunrise and sunset.

Similar differences between transmission at midday and the beginning and end of the day have been reported previously (Gueymard, 1989; Heuvelink *et al*., 1995).

One possible explanation for the differences in the first half of the day could be the presence of dust and condensation on the internal side of the glass pane. While the simulation model assumed 'ideal' conditions, in practice it was impossible to eliminate these factors completely, despite the efforts made to reduce them. The higher proportion of diffuse radiation compared with total radiation at sunrise and sunset due to the low elevation of the sun was not considered in the simulation model. Diffuse radiation during these periods may have been responsible for an increase in the measured radiation, which tended to compensate for the potential reduction in radiation due to the presence of dust and condensation.

Regression coefficients are shown in Table 2, which shows that the slope of the regression lines for greenhouse models with a low roof angle was always less than 1·1 and the regression coefficients were close to 0·9. On all dates except 25th April, as the roof slope increased, the slope of the regression lines increased as well or remained invariable, which means that agreement between measurement and simulation was worse. The exception of 25th April may have been due to an error deriving from the fact that the model does not consider second degree reflexions, which may be relevant with respect to the total transmission obtained when slopes are very pronounced. Previous research (Kurata, 1990) pointed out the importance of second-order reflection in east–west greenhouses. Schultz (1955) also remarked upon the contribution of the radiation reflected by the north side of the roof. The maximum difference corresponded to the greenhouse roof with slopes 27-45° (the south-facing slope was 27° and the north-facing one was 45°); the predictions from the simulation model for this case exceeded measurements by 12%.

3.3. Comparison of mean daily transmission

The trend observed for mean half-hour values also held true for daily transmission values [Figs 4(*a*), (*b*) and (*c*)]: the predictions from the simulation model exceeded measurements for all roof slopes under study and for all seasonal periods considered and differences increased as the roof slope increased. As shown in Table 3, the calculated mean daily transmission was approximately 6% higher than that measured for the 8-18° scale model and about 10% higher than that measured for the 27-45° and 36-55° models. This difference was slightly lower than that found in other models validating transmission in greenhouses (Baille & Baille, 1990, Li *et al*., 1995) and was considered acceptable for the purpose of comparing or designing roof shapes to provide more efficient radiation transmission. The highest standard errors are also associated with the scale model with highest slope on the north-facing side (36-55° and 27-45°).

Calculation of the statistical parameters D_{MB} and D_{RMS} (Table 4) also illustrates the tendency of the scale models to systematically produce lower transmission values than those from the simulation models. Again, the associated errors were the lowest in the case of the greenhouse with the least slope. An

interesting point to be observed in Table 4 is that the D_{MB} and D_{RMS} were nearly the same in the 2 yr of measurements, which is proof of the reliability of the experimental design.

3.4. Direct radiation transmission in scale models with different slopes

For the summer solstice, the two models with the gentlest slopes presented the highest transmission (75% for 18-8° and 71% for 27-27°). This difference in transmission was not important (offers no practical value for the growers), however, since shade is usually used to reduce summer radiation in Mediterranean climates in an attempt to mitigate high temperatures. As autumn advances, and both the maximum altitude of the sun on the horizon and day length correspondingly decrease, this situation is inverted. For instance, at the equinoxes transmission tended to increase as the roof slope increased. Maximum differences can be found around the winter solstice, when the roof with the least slope (18-8°) had a transmission power of 59%, while the one with 45-27° had 66%.

A case that deserves special attention is the 27-27° symmetrical roof. This scale model had the highest winter transmission among all the cases compared in Table 5. This fact can be explained by considering the transmission curve for glass (Fig. 2), which shows transmission to be nearly constant for angles of incidence less than approximately 45°. If roof slopes 27-27° and 45-27°N at the latitude of the experimental site (37°N) are compared, the angle of incidence of beam radiation for both southern surfaces (27 and 45°) was less than this critical value of 45° for most of the hours around midday. Their transmission was therefore almost identical. Nevertheless, the length of the south surface for any given span width was bigger for the 27° case and, consequently, the amount of solar energy received along the south surface (and thus transmission through the south surface) was also greater. Another potential advantage of this symmetrical roof is uniform transmission throughout the year. According to Table 5, seasonal variation in transmission was highest for the roof with the least slope (18-8°), and tended to diminish as roof slope increased.

4. Conclusions

The use of scale models is a valid method for characterising direct-radiation transmission in greenhouses with different roof angles, since measurements agreed well with predictions from a simulation model. Better agreement between measured and simulated values was found for models with less roof slope.

For the latitude studied in this article, increased roof slope improved direct radiation transmission around the time of the winter solstice, up to a certain value beyond which it once more declined. In summer, however, lower roof angles corresponded to the highest transmission levels.

Asymmetrical greenhouses do not necessarily provide greater transmission than symmetrical ones. An east–west oriented greenhouse with a roof slope of 27° had the highest transmission of all the models considered in this study.

The use of scale models for studying transmission is a simple and economical method and can be a useful tool for designing greenhouses with enhanced radiation transmission.

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Fig. 1. East–west oriented 1:15 greenhouse models at the experimental site (latitude 37° 10′N), south of Spain, with the south-facing and north-facing slopes shown for each model

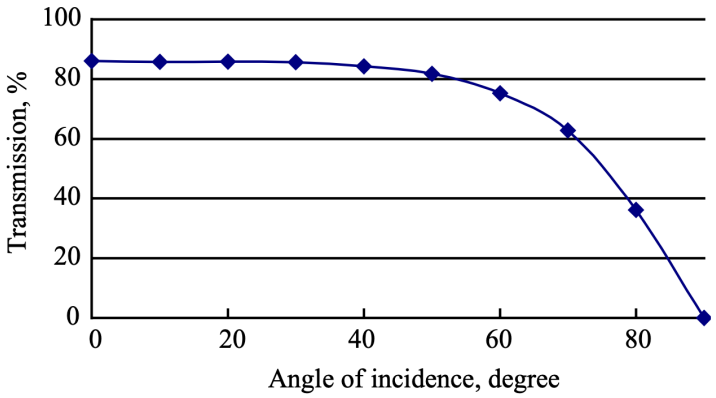

Fig. 2. Laboratory measurement of direct radiation transmission through glass samples as a function of the angle of incidence

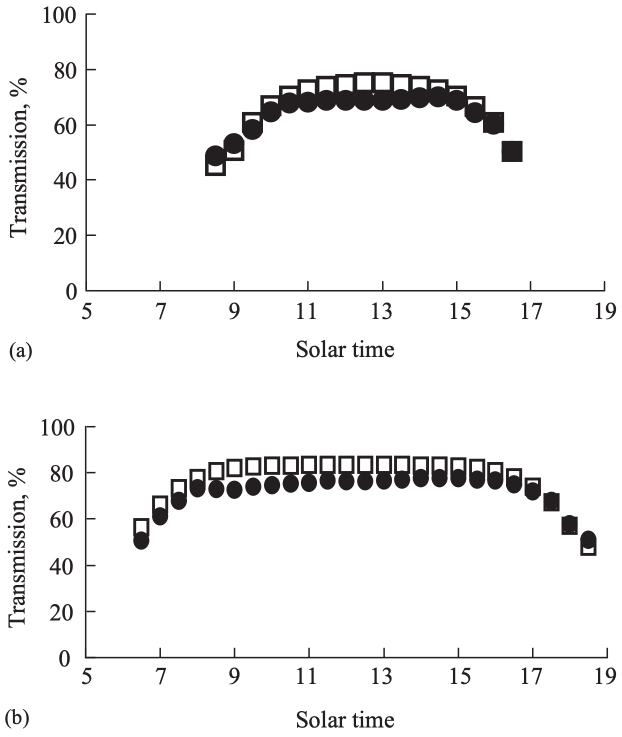

Fig. 3. Comparison of mean half-hour transmission values simulated by the model and measured in the 8-18° scale model (8-18° means that the south-facing slope was 8° and the north-facing one was 18°) on two dates: (a) 13th January; (b) 19th June; measurements taken under clear-sky conditions; □, simulated values; •, measured values

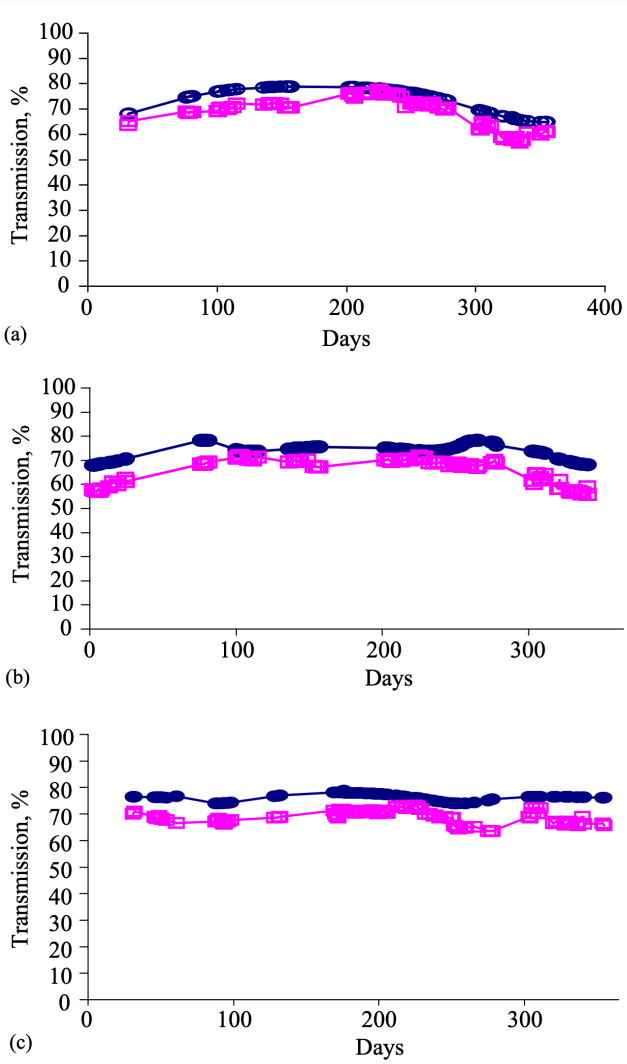

Fig. 4. Comparison of measured and simulated mean daily transmission: (a) 18-8° scale model; (b) 36-55° scale model; (c) 45-27° scale model (18-8° means that the south-facing slope was 18° and the north-facing one was 8°); o, simulated values; □, measured values in scale models

Table 1. Roof slopes of the tested scale models: *α* on the south surface and *β* on the north surface

Scale model	*Roof angle, deg*	
	South–facing slope (*α*)	*North–facing slope* (*β*)
1	8	18
2	18	8
3	27	45
4	45	27
5	36	55
6	55	36
7	27	27

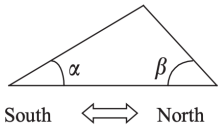

Table 2. Slope of the regression line and regression coefficient between measured and calculated transmission values for the scale models on four clear days

Date	*Roof angle, deg*		*Regression line slope*	*Regression coefficient*
	South-facing slope (*α*)	*North-facing slope* (β)		
13th Jan	8	18	1·05	0·93
	27	45	1·12	0·96
	36	55	1·11	0·76
25th Apr	8	18	1·09	0·87
	27	45	1·1	0·86
	36	55	1·05	0·96
19th Jun	8	18	1·05	0·93
	27	45	1·07	0·87
	36	55	1·07	0·75
16th Sep	8	18	1·02	0·98
	27	45	1·07	0·94
	36	55	1·1	0·82

Table 3. Mean yearly ratio between measured and simulated mean daily transmission for different roof slope models. Standard error of the ratio

Roof angle, deg		*Measured transmission / simulated transmission*	*Standard error*
South-facing slope (*α*)	*North-facing slope* (*β*)		
8	18	0·94	0·0200
18	8	0·93	0·0197
27	27	0·91	0·0189
27	45	0·90	0·0219
36	55	0·90	0·0432
45	27	0·91	0·0184
55	36	0·92	0·0185

Table 4. Mean bias deviation (D_{MB}) in % and root-mean-square deviation (D_{RSM}) of the yearly mean of mean daily transmisión

Roof angle, deg		*Mean bias deviation, %*		*Root mean square deviation, %*	
South-facing slope (*α*)	*North-facing slope* (*β*)	*1998*	*1999*	*1998*	*1999*
8	18	6·9	6·6	7·2	7·7
18	8	7·7	7·9	8·6	8·6
27	27			10	10·4
27	45			12·4	12·7
45	27	10·4	10·5	10·7	11
36	55			12·1	13·4
55	36	8·2	8	8·6	8·2

Table 5. Mean seasonal transmission and maximum differences throughout the year for four roof angle scale models with different roof slopes

Roof angle, deg		*Seasonal transmission, %*			
South-facing slope (*α*)	*North-facing slope* (*β*)	*Summer solstice*	*Equinox*	*Winter solstice*	*Maximum difference*
18	8	74·9	69·8	59	15·9
36	55	69·7	66·3	56·7	13·0
45	27	71·3	67·7	66·6	4·7
27	27	71	68·5	70·1	0·9